ULTRA-LOCAL TEMPERATURE MAPPING WITH AN INTRINSIC THERMOCOUPLE

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ABSTRACT

We report on a set-up derived from an Electrostatic Force Microscope (EFM) allowing us to probe temperature with a high spatial resolution. The system uses the well-known Seebeck effect through an intrinsic thermocouple made from an EFM conducting tip put in contact with a conducting sample. The contact radius between tip and sample is currently estimated to be in the 50 to 100 nm range depending on the elastic or the plastic deformation. The contact area can be assimilated to the electrical and thermal contact areas. In those conditions, the issue of heat conduction in air is solved. The thermal measurement is related to the Seebeck junction effect: it will therefore not be sensitive to buried materials or impurities.

1. INTRODUCTION

Temperature and heat flux measurements at submicrometer scales have a broad range of applications related for instance to semiconductor devices, chemical reactions and phase transformations. Existing techniques include thermoelectric probes such as thermocouples, semiconductor diodes and thermistors. Optical techniques such as infrared thermometry[1] and surface reflectometry[2] are also state-of-the-art tools. A quite recent metrology is based on a thermocouple or a thermoresistive probe mounted in an Atomic Force Microscope (AFM)[3-9]. It provides thermal and topographical images of sample surfaces with high spatial resolution. The accuracy and the spatial resolution of those measurements are however affected by three main parameters: the coupling between the thermal and topographical signals, the heat transfer in air which spreads the thermal contact over a micrometer scale and the thermal conductivity of the studied materials or of the sub-surface materials. This very last case influences the measurement when the penetration depth of the thermal signal is comparable or greater than the contact radius.

In this paper, we report on the modification of the EFM as a SThM by using a tip contacting a metallic heating surface. The local probing is based on the Seebeck effect. Local investigation seems easy because the radius of the contact between the tip and the sample is estimated to be in the 50-100 nm range depending on the applied contact force. The contact radius can be roughly assimilated to the electrical and thermal contact radii. The heat conduction through the air can be neglected (it is not the case for adsorbed layers). Because the thermal measurement is based on the Seebeck junction effect, surface effects are predominant. The system will therefore not be sensitive to buried materials or impurities. The Debye length (a few nanometers) defines the limit of the measurement area.

Our sample is a CMOS chip including an aluminum top layer. Resistors are buried and will allow us to heat surfaces of various sizes. The temperature calibration is performed with an in-situ sensor. A judicious choice of conducting material for the tip makes it possible to obtain an optimized thermoelectric couple.

We present the temperature calibration obtained with our set-up with different thermoelectric couple.

2. THE EXPERIMENTAL SET-UP

The set-up is derived from an Electrostatic Force microscope (EFM)[10,11] using a conductive tip in contact with the sample under test (figure 1).

The conductive probe is made with a silicon cantilever with a stiffness K_C = 150 N/m (Length = 7 mm, Width =

400 µm and thickness = 150 µm) associated with a diamond tip of 2µm in radius.

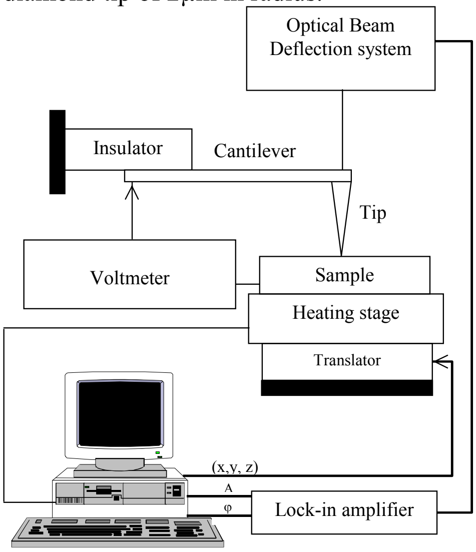

Figure 1: experimental set-up for local temperature probing derived from an EFM.

A thin layer of a conductive material is deposited by magnetron sputtering on the assembly to obtain a conductive tip. The set-up uses the classical Optical Beam Deflection method to control the contact force between the tip and the sample. In a first time, in order to perform these measurements the EFM has been implemented with a low cost and single heating stage. This stage is described in figure 2.

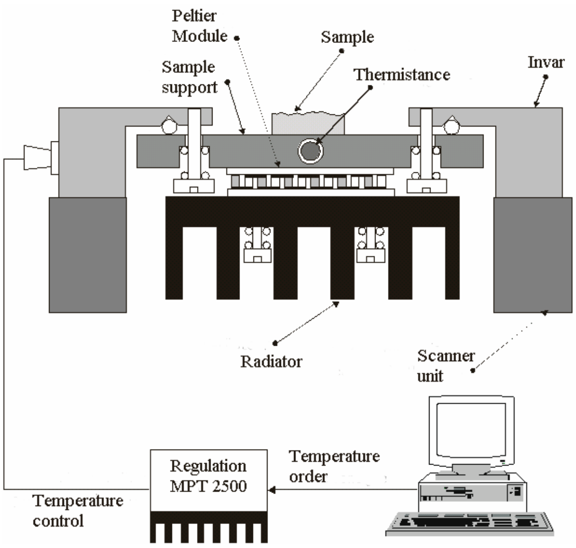

Figure 2: Principle of the heating stage

The heater is a Peltier module, which allows to modify the temperature with an electric current. It is possible to heat or cool the sample with this classical thermal system, and it is necessary to use a radiator to evacuate the heat. Moreover we use a thermistance (TCS 605) to measure the instantaneous temperature. To minimize the thermal drifts, the heater system has been realized in aluminum and Invar (the thermal expansion coefficient of Invar is very low). The Invar part holds the support sample by nylon screws and springs. By this way the differential expansion is directed towards the radiator and the induced displacement on the sample is minimum. This specific stage enables to obtain a mechanical drift below 50 nm/°C, and a temperature range above 100 °C.

3. THEORETICAL BASIS

3.1. The Seebeck effect

In 1821, Thomas Johan Seebeck made the discovery that the creation of an electrical voltage was possible by the difference between two metals having different conductive properties at the other end of the two wires. The Seebeck effect is the heart of thermocouples: if two metals having different Seebeck coefficients are jointed together at one end the presence of a voltage called Electromotive Force (EMF) will be apparent using a voltmeter at the other end. This voltage is due to the temperature gradient between the two sides.

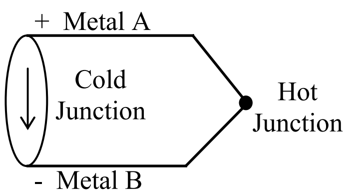

Figure 3: basic principle of the thermocouple.

As mentioned earlier, this instrumentation will involve the use of the conductive tip of an EFM microscope (Metal A) and a metallic sample (Metal B) for the “fabrication” of an intrinsic thermocouple. The hot junction will be the contact point between the tip and the sample, giving the possibility to perform ultra local temperature measurement. The main effect that is predominantly applicable is the Seebeck effect, where an electromotive force is formed as a result of the proportionality of the thermal gradient between the hot and cold junction materials. The change in voltage between the two junctions is described by taking an integral over the starting / reference temperature to the final temperature. This is shown by the following equation:

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$$\Delta V=\int_{T_0}^{T} S.dT \tag{1}$$

Which simplifies to $E=S_{A-B}\times\Delta T$
(Keep in mind that this is true for one thermal couple).
S_{A-B} is the Seebeck coefficient difference between the two metals. The Seebeck coefficient is a material property that is temperature dependant and can be found by $S=\frac{dV}{dT}$.
In metals the Seebeck coefficient is given by the Mott-Jones equation[12]:

$$S \approx -\frac{\pi^2 k_B^2 T}{3qE_{F0}} x \tag{2}$$

With k_B the Boltzmann's constant, T the temperature in Kelvin, x a numerical constant dependant on charge transport mechanism, q the charge of an electron, and E_{F0} the Fermi energy at 0K. Table1 gives the thermal characteristics of some materials.

Metal	S at 0°C (µV/K)	S at 27 °C (µV/K)	E_{F0} (eV)	x
Al	-1.6	-1.8	11.6	2.78
Au	+1.79	+1.94	5.5	-1.48
Cu	+1.70	+1.84	7	-1.79
Pt	-4.45	-5.28		

Table1: Seebeck coefficients of selected metals

3.2. The contact point: the hot junction

The contact between the conductive tip and the metallic sample can be considered as the hot junction of the thermocouple. To estimate the size of the contact area, we assumed that the contact is in the elastic regime and we use the classical Hertzian theory. This theory allows to calculate the radius *a* of the contact area by this formula[13]:

$$a=\left(\frac{3FR}{4E^*}\right)^{1/3}$$

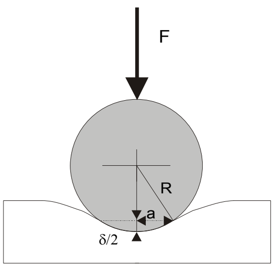

Figure 4: The hertzian contact model.

With F the contact force, R the radius of the tip and E^* the composite Young's modulus given by the following expression:

$$\frac{1}{E^*}=\frac{1-\nu_t^2}{E_t}+\frac{1-\nu_s^2}{E_s}$$

Where E_t, ν_t and E_s, ν_s are respectively the Young's modulus and Poisson ratio of the tip and sample.
In our set-up we use a tip with a 2 µm radius. the standard contact force applied on the sample is estimated by using the stiffness of the associated microcantilever (K_C) and by a variable offset displacement Δz of the sample ($F=K_C\Delta z$).
Table2 gives the radius of contact for the metallic samples investigated in the case of two contact forces.

Metal	Contact radius at F = 75 µN	Contact radius at F = 150 µN
Al	113.05 nm	142.43 nm
Cu	94.52 nm	119.09 nm
Ni	87.95 nm	110.8 nm

Table 2: contact radius for different samples

These calculations demonstrate that with this intrinsic thermocouple method it is possible to perform ultra-local thermal measurement with a resolution of about 100 nm considering that this radius can be assimilated to the electrical and thermal contact radius.

4. EXPERIMENTAL RESULTS AND DISCUSSION

The results have been obtained with different thermoelectric couples. We have used two conductive tips made by a thin layer of gold and platinum. Different samples have been investigated such as aluminum, copper and nickel. The figure 5 presents the emf variations obtained with the gold and platinum tips for an aluminum sample versus temperature.

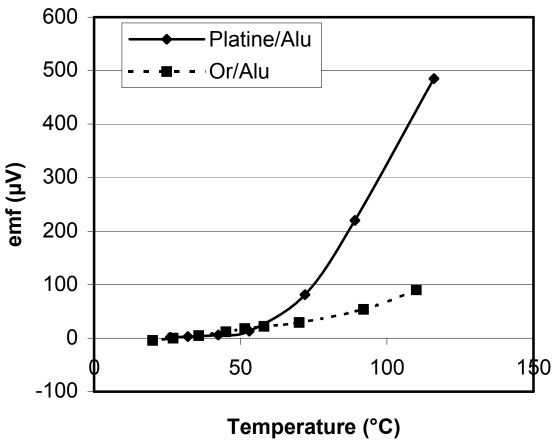

Figure 5: Detected emf in the case of an aluminum sample with to different tips (gold and platinum).

The figure 6 shows the results obtained in the case of a copper sample.

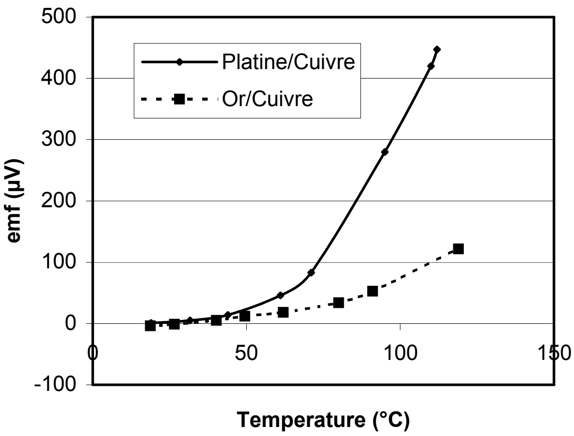

Figure 6: Detected emf in the case of a copper sample with to different tips (gold and platinum).

As expected we demonstrate that the emf voltage variations detected in all the cases depend on the temperature variations. The results are different with the platinum tip compared to those obtained with the gold tip as predicted by the difference in thermoelectric properties of these materials. Nevertheless on these first results we can see that with the same tip but with different samples the evolution of the emf voltage is quite similar. Further investigations are in progress in order to explain this low sensitivity to the sample material.

In a second set of experiments a specific sample, which is a CMOS chip including an aluminum top layer has been investigated. Resistors are buried and allow us to heat aluminum surfaces of different sizes (metal 4). A view of the chip and a scheme of the specific structure under test are given in figures 7a and 7b.

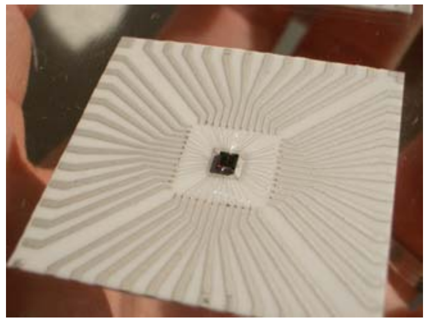

Figure 7a: a view of the specific CMOS chip

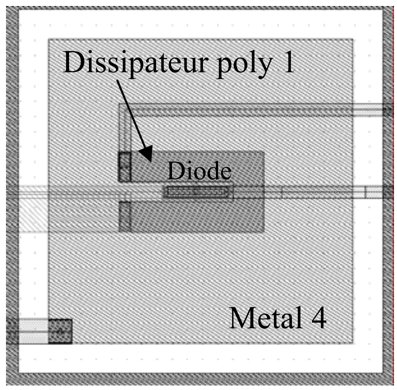

Figure 7b: Scheme of the structure investigated

The temperature calibration is performed with an in-situ diode sensor.
Figure 8 shows the response of the diode sensor versus the heat current variation in the resistors.

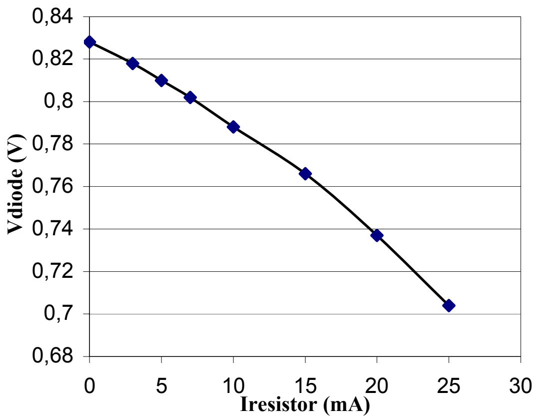

Figure 8: Forward diode voltage versus heating current in the tested sample.

From these results we have calibrated the temperature variation obtained by joule effect. We have a temperature variation of 27 °C to 72°C for a current variation of 25 mA in the resistor. We have performed the measurement with the gold tip and as expected the detected emf variation increases as the temperature increases until 72 °C (figure 9).

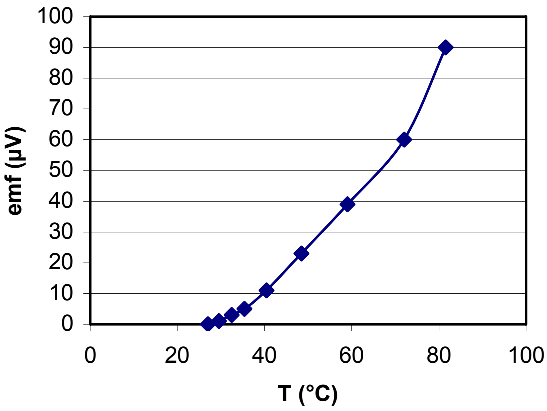

Figure 9: Seebeck voltage detected with a gold contacting tip versus heating current

On the same way the emf magnitude measured in this experiment is very close to the one measured in the first experiment with the peltier module and the bulk aluminum sample demonstrating the repeatability of the measurement.

5. CONCLUSION

This communication reports on our first results concerning the use of an intrinsic thermocouple to perform ultra-local temperature measurements. The intrinsic thermocouple made from an EFM conducting tip put in contact with a conducting sample use the well-known Seebeck effect. The first results demonstrate that is possible to measure the temperature variation of the sample in contact with the conductive tip by detecting the net emf voltage. We have successfully used this method on a specific CMOS chip showing that this method could be an interesting tool for thermal measurement on IC devices. Further investigations are in progress on this method in order to completely analyze the behavior of this intrinsic thermocouple.

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